

# **Implications of right-handed neutrinos with electroweak-scale masses**

P. Q. Hung

*Dept. of Physics, University of Virginia, 382 McCormick Road, P. O. Box 400714,  
Charlottesville, Virginia 22904-4714, USA*

## **Abstract**

The possibility of constructing a model in which right-handed neutrinos have electroweak-scale masses as well as being *non-sterile* was espoused in <sup>1)</sup>. In this talk, I will review the ideas and results of <sup>1)</sup> and discuss its implications for colliders such as the Tevatron, LHC and ILC.

## 1 Introduction

The origin of neutrino masses and the puzzle over their smallness are two of the outstanding questions in particle physics. Of related importance is the nature of the neutrinos: Are they Dirac or Majorana particles? There is no doubt about the importance that neutrinos have in particle physics and cosmology: The understanding of their masses unquestionably points to features that cannot be explained by staying strictly within the Standard Model (SM) such as, for example, the baryon number asymmetry which might arise through the so-called leptogenesis coming from the decay of a heavy Majorana neutrino. Furthermore, results from neutrino oscillation data indicated a mixing matrix in the lepton sector which is markedly different from that coming out of the quark sector. One cannot help but wonder if, despite this dissimilarity, the two sectors can “learn” from each other.

Neutrino masses are believed to be tiny compared with other fermion masses, of order  $O(< 1\text{ eV})$ . Why this is so is one of the biggest mysteries which we are trying to unlock. The “simplest” way to give a mass to the neutrino is to add a SM singlet right-handed neutrino to the SM and give it a Dirac mass. However, to account for the smallness of the neutrino masses, Yukawa couplings of  $O(10^{-11})$  have to be put in *by hand*. This is generally considered to be unnatural unless there are dynamical or symmetrical reasons for it to be so<sup>2)</sup>. The by-far most popular scenario is the quintessential see-saw mechanism<sup>3)</sup> where, in addition to the Dirac mass ( $m_D$ ) term which couples left- and right-handed neutrinos, a lepton-number-violating Majorana mass ( $M_R$ ) term for the right-handed (the simplest version) neutrinos is written down. In the “standard” see-saw mechanism, this Majorana mass term is *huge* compared with the Dirac mass term (which is proportional to the electroweak scale) resulting in a tiny mass  $\sim m_D^2/M_R$  for the lighter of the two eigenstates. The right-handed neutrinos being sterile in this scenario and being extremely heavy are practically undetectable, at least directly. Therefore, in its simplest version, one just cannot directly verify the see-saw mechanism since one cannot detect the right-handed neutrinos. Are there other ways?

Since, within the framework of see-saw scenarios, the light neutrino sector is only sensitive to the ratio  $m_D^2/M_R$ , it is legitimate to ask how one can change  $m_D$  and  $M_R$  in such a way as to keep  $m_D^2/M_R$  unchanged. The question is the following: Could one lower both of them in such a way as to make  $M_R$  slide into a region, in particular around the electroweak scale, where one could have an access to the right-handed neutrino sector? This is one of the motivations for the construction of a model of electroweak-scale right-handed neutrino mass<sup>1)</sup>. The organization of the talk will be as follows. First, a brief review of the see-saw mechanism will be presented. Next, we will present arguments on why the right-handed neutrinos can be as light as or lighter than the electroweak

scale. We then discuss the implications of electroweak-scale  $\nu_R$ 's, including the production and decays of  $\nu_R$ 's as well as lepton-number violating processes at colliders. A conclusion will follow the phenomenological discussion.

## 2 The see-saw mechanism in a nutshell

In the “standard” see-saw scenarios<sup>3)</sup>,  $\nu_R$ 's are SM *singlets* and are commonly termed *sterile*. This has obviously deep implications on the nature and sizes of the Dirac and Majorana masses.

- Dirac Mass:

The neutrino Yukawa interaction with a sterile right-handed neutrino which gives rise to the Dirac mass term is usually written as

$$\mathcal{L}_D = g_L \bar{l}_L \phi \nu_R + H.c., \quad (1)$$

where  $l_L = (\nu_L, e_L)$  and  $\phi = (\phi^0, \phi^-)$  are the usual SM  $SU(2)_L$  doublets. When  $\langle \phi \rangle = (\Lambda_{EW}/\sqrt{2}, 0)$  with  $\Lambda_{EW} \approx 246 \text{ GeV}$ , one obtains the following the neutrino Dirac mass

$$m_D = g_L \Lambda_{EW} / \sqrt{2}. \quad (2)$$

In consequence, the Dirac mass is proportional to the electroweak scale  $\Lambda_{EW}$ , although it crucially depends on an arbitrary Yukawa coupling  $g_L$ . It is worth to emphasize again that this is the case because  $\nu_R$  is a SM singlet. We will see below that when  $\nu_R$  is *not* a SM singlet, the Dirac mass will no longer be related to  $\Lambda_{EW}$ .

- Majorana mass:

The source of the right-handed neutrino Majorana mass is quite model-dependent, although it is commonly found within the framework of a Grand Unified Theory (GUT). In what follows, we will write it simply as

$$\mathcal{L}_M = M_R \nu_R^T \sigma_2 \nu_R. \quad (3)$$

The above Majorana mass term violates lepton number by two units.

- Mass eigenvalues:

The two well-known eigenvalues are  $\sim -m_D^2/M_R$  and  $M_R$  for  $M_R \gg m_D$ . The two neutrino mass eigenstates which are now Majorana particles are approximately the left-handed neutrino for the lighter state and the right-handed neutrino for the heavy state. Since  $m_D$  is proportional to the electroweak scale (modulo the unknown Yukawa coupling), a light neutrino with mass of order  $O(< 1 \text{ eV})$  in general requires  $M_R$  to be of

order  $O(\sim 10^{13} \text{ GeV})$ . In this type of scenarios, one just *cannot directly* detect the right-handed neutrinos.

Since neutrinos (both the light state and the heavy state) are now Majorana particles, it is therefore of utmost importance to test this feature of the model. One should look for processes that violate lepton number conservation. In the light sector, one could look for neutrinoless double beta decay for example which gives an upper bound, not on the mass of the light state, but on the combination  $\langle m_{\beta\beta} \rangle = [\sum |U_{ei}|^2 m_i^2]^{1/2} < 0.35 \text{ eV}$ , where  $m_i$  are the light masses<sup>4)</sup>. This search is not easy because of various nuclear details. This is where the right-handed neutrino sector comes in if the right-handed neutrinos are light enough. As for the heavy sector, at least in its simplest version, there is no such a possibility for testing the Majorana nature of the right-handed neutrinos. Electroweak-scale SM *singlet* right-handed neutrinos were contemplated as a possibility which could enable one to probe the right-handed sector. There are however a number of delicate issues with these scenarios which might prevent its observability unless some fine tuning is realized<sup>5)</sup>. An extensive list of references of works dealing with “light” right-handed neutrinos can be found in<sup>5)</sup>.

Can the right-handed neutrinos be *non-sterile*? If one can construct such a scenario then one can hope to be able to find them at colliders and test the Majorana nature of neutrinos. In what follows I will describe a model in which right-handed neutrinos are both “light”, i.e. having electroweak-scale masses, and “observable”, i.e. transforming non-trivially under the SM gauge group.

### 3 A Model of electroweak-scale right-handed neutrino mass

The objective of<sup>1)</sup> was to construct a model in which  $\nu_R$ 's are *not* sterile and have a *low* mass of  $O(\Lambda_{EW})$ . There are two constraints that have to be satisfied in the construction of such a model.

- A non-sterile  $\nu_R$  will couple to the Z boson. There is however a strong constraint from the Z width: There are only *three* light left-handed neutrinos.
- A Majorana bilinear  $\nu_R^T \sigma_2 \nu_R$  will transform *non-trivially* under  $SU(2)_L \otimes U(1)_Y$ . This imposes a strong constraint on the Higgs field which couples to that bilinear and which develops a non-zero vacuum expectation value, namely one has to preserve the successful relation  $M_W = M_Z \cos \theta_W$ !

As we shall see below, the first constraint sets a *lower bound* on the right-handed neutrino mass while the second will determine the enlargement of the Higgs structure of an extended SM.

The simplest possibility and the one that was used in <sup>1)</sup> is to put  $\nu_R$  into a doublet of  $SU(2)_L$ . If it belongs to a doublet then its partner would be a *negatively* charged right-handed lepton. Could it be the right-handed SM charged lepton? The answer is negative because neutral current experiments have shown that the SM right-handed charged leptons are  $SU(2)_L$  singlets. In consequence, this right-handed charged lepton has to be a new type: the so-called *mirror* lepton. We write this new doublet as follows

$$l_R^M = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix}, \quad (4)$$

where now the left-handed charged mirror lepton, namely  $e_L^M$ , is a SM singlet. So, the above doublet plus  $e_L^M$  will be the mirror copy of the SM doublet  $l_L = (\nu_L, e_L)$  and  $e_R$ .

In a similar fashion to the “standard” see-saw scenario, one can write down the interactions which will give a Dirac mass term for the neutrino and a Majorana mass term.

- Dirac mass:

A Dirac mass term for the neutrino is proportional to  $\bar{l}_L l_R^M$ . This combination can couple to a SM *singlet* scalar field  $\phi_S$  as follows

$$\mathcal{L}_S = g_{Sl} \bar{l}_L \phi_S l_R^M + H.c. \quad (5)$$

When  $\phi_S$  develops a non-vanishing VEV, namely  $\langle \phi_S \rangle = v_S$ , the neutrino Dirac mass takes the form

$$m_D = g_{Sl} v_S. \quad (6)$$

In this model, the Dirac mass is *not* linked to the electroweak scale. We will see below the range of values that  $v_S$  can take.

Notice that for the charged fermions (leptons and quarks), there are additional couplings to  $\phi_S$  involving the  $SU(2)_L$  singlets of the forms  $\bar{f}_L^M f_R$ , where  $f$  stands for  $q$  or  $e$ . For simplicity, one can assume similar Yukawa couplings to the ones given in the above form. This yields the mixing given in <sup>1)</sup>. There it was shown that the mixing between SM and mirror charged fermions is *negligible*.

- Majorana mass:

In our model, the lepton-number violating relevant fermion bilinear is  $l_R^{M,T} \sigma_2 l_R^M$ . This transforms as a singlet and as a triplet of  $SU(2)_L$ . A singlet Higgs field which couples to this bilinear and which develops a

VEV would break charge conservation. The only other option is a triplet Higgs  $\tilde{\chi} = (3, Y/2 = 1)$  which is written explicitly as

$$\tilde{\chi} = \frac{1}{\sqrt{2}} \vec{\tau} \cdot \vec{\chi} = \begin{pmatrix} \frac{1}{\sqrt{2}} \chi^+ & \chi^{++} \\ \chi^0 & -\frac{1}{\sqrt{2}} \chi^+ \end{pmatrix}. \quad (7)$$

which couples to the bilinear as follows

$$\mathcal{L}_M = g_M l_R^{M,T} \sigma_2 \tau_2 \tilde{\chi} l_R^M. \quad (8)$$

With  $\langle \chi^0 \rangle = v_M$ , the Majorana mass is now

$$M_R = g_M v_M. \quad (9)$$

The above VEV breaks  $SU(2)_L$ . The successful relation  $M_W = M_Z \cos \theta_W$  ( $\rho = 1$  at tree level) which relies primarily on  $SU(2)_L$  Higgs fields being doublets would be spoiled unless  $v_M \ll \Lambda_{EW}$ . This is a severe constraint that needs to be addressed in our model.

An important remark is in order here. In order to prevent the left-handed neutrinos to acquire a Majorana mass of the same order as the right-handed one as well as to prevent a large Dirac mass (coupling of  $\bar{l}_L l_R^M$  to  $\tilde{\chi}$ ), a global  $U(1)_M$  symmetry is imposed<sup>1)</sup> (and explicitly broken by the Higgs sector). A tiny Majorana mass for the left-handed neutrinos arises at one-loop level<sup>1)</sup>.

An elegant solution to this problem was provided about twenty years ago by<sup>6)</sup>: If the Higgs potential which now includes triplet scalars possesses a custodial symmetry such that  $M_W = M_Z \cos \theta_W$  is preserved at tree-level then the triplet VEV's can be as large as the electroweak scale.  $\rho = 1$  is therefore the manifestation of an approximate *custodial* global  $SU(2)$  symmetry of the Higgs potential. To maintain that *custodial symmetry*, one can add an additional Higgs triplet  $\xi = (3, Y/2 = 0)$  which can be grouped with  $\tilde{\chi} = (3, Y/2 = 1)$  to form

$$\chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix}, \quad (10)$$

where the full potential now exhibits a global  $SU(2)_L \otimes SU(2)_R$  symmetry. The following VEV of  $\chi$  breaks  $SU(2)_L \otimes SU(2)_R$  down to a custodial  $SU(2)$  symmetry

$$\langle \chi \rangle = \begin{pmatrix} v_M & 0 & 0 \\ 0 & v_M & 0 \\ 0 & 0 & v_M \end{pmatrix}. \quad (11)$$

This gives

$$M_W = g v/2; M_Z = M_W/\cos\theta_W, \quad (12)$$

with

$$v = \sqrt{v_2^2 + 8 v_M^2}, \quad (13)$$

and

$$\langle\Phi\rangle = v_2/\sqrt{2}, \quad (14)$$

where  $\Phi$  is a doublet. The nice feature of this scenario is the fact that now  $v_M$  *can* be of the order of the electroweak scale *without* spoiling  $\rho = 1$ . As discussed in <sup>1)</sup>, there are no massless NG bosons in this model since  $U(1)_M$  is explicitly broken.

The upshot of all this is the following nice result

$$M_R \sim O(\Lambda_{EW}). \quad (15)$$

The right-handed neutrino mass can now be *naturally* of the order of the electroweak scale (but not more)!

How low can  $M_R$  be? A right-handed neutrino with a mass lower than half the Z-boson mass would contribute to the Z width with the amount as the left-handed one. This is ruled out experimentally. We therefore conclude that  $M_R$  lies in a rather “narrow” range

$$M_Z/2 < M_R < \Lambda_{EW}. \quad (16)$$

- Estimate of the singlet Higgs VEV:

With the light neutrino mass  $m_\nu \leq 1 \text{ eV}$  and  $M_R \sim O(\Lambda_{EW})$ , one can get a rough estimate on the singlet VEV by putting  $g_{SL} \sim O(1)$  to give

$$m_D \sim v_S \sim 10^5 \text{ eV}. \quad (17)$$

A small scale such as  $v_S$  is interesting in many respects. First there appears to be some kind of hierarchy problem since  $v_S$  is six orders of magnitude smaller than  $v_M$ , although it is not as severe as the GUT hierarchy problem. However, one can imagine that  $v_S$  might actually be the *present* classical value of the singlet Higgs field  $\phi_S(t_0)$  whose effective potential might be of a “slow-rolling” type. This type of scenario was proposed in a mass-varying neutrino (MaVan) model of the first reference of <sup>7)</sup>. The Dirac will keep increasing until  $\phi_S$  reaches the true minimum which could be of the order of the electroweak scale itself!

What (15) and (17) tell us is that, in our scenario, the mass scales participating in the see-saw mechanism are slid “downward” with respect to the “standard” see-saw scenario, but now there is one phenomenological advantage: One can now search for the right-handed neutrinos at colliders. As we have mentioned above, the light neutrinos are only sensitive to the ratios  $m_D^2/M_R$  and not directly to the scale  $m_D$ . A discovery of an electroweak-scale right-handed neutrino would greatly help us determine what  $m_D$  should be. We now turn to the discussion on the detectability of the electroweak-scale right-handed neutrinos.

#### 4 Phenomenology of Electroweak Scale $\nu_R$ ’s

Since we are dealing with *Majorana neutrinos* with electroweak scale masses, it is not surprising that we should expect lepton-number violating processes at electroweak scale energies. In particular, we should be able to produce  $\nu_R$ ’s and observe their decays at colliders (LHC, etc...). The characteristic signatures will be *like-sign dilepton* events which are a high-energy equivalent of neutrinoless double beta decay.

Since  $\nu_R$ ’s are members of  $SU(2)_L$  doublets  $l_R^M = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix}$ , they interact with the Z and W bosons. They are *no longer* sterile! Let us now recall that we have the constraint  $M_Z/2 < M_R < \Lambda_{EW}$ . This means that, in principle,  $\nu_R$ ’s can be produced at colliders, being sufficiently light. Unlike the case with low-mass singlet  $\nu_R$ ’s whose production at colliders could be suppressed, the right-handed neutrinos in our scenario couple directly to the Z boson and the production of a pair of  $\nu_R$ ’s is unsuppressed. One has

$$q + \bar{q} \rightarrow Z \rightarrow \nu_R + \nu_R. \quad (18)$$

Since  $\nu_R$ ’s are Majorana particles, they can have transitions such as  $\nu_R \rightarrow l_R^{M,\mp} + W^\pm$ . A heavier  $\nu_R$  can decay into a lighter  $l_R^M$  and one can have

$$\nu_R + \nu_R \rightarrow l_R^{M,\mp} + l_R^{M,\mp} + W^\pm + W^\pm \rightarrow l_L^\mp + l_L^\mp + W^\pm + W^\pm + \phi_S + \phi_S, \quad (19)$$

where  $\phi_S$  would be missing energy. This gives rise to interesting *like-sign* dilepton events. Since this involves missing energy, one would have to be careful with background. For example, one of such background could be a production of  $W^\pm W^\pm W^\mp W^\mp$  with 2 like-sign W’s decaying into a charged lepton plus a neutrino (“missing energy”). But...This is of  $O(\alpha_W^2)$  in amplitude smaller than the above process. In addition, depending on the lifetime of the mirror leptons, the SM leptons appear at a displaced vertex. Lepton-number violating process with like-sign dileptons can also occur with  $\nu_R$ ’s in the intermediate state (from  $W^\pm W^\pm \rightarrow l_L^\pm + l_L^\pm$ ) but that involves very small mixing angles of the order  $\frac{m_\nu}{M_R}$ .



In consequence, within the framework of our model, one has the interesting prospect of producing and detecting electroweak-scale right-handed neutrinos through lepton-number violating processes such as like-sign dileptons as described above. Detailed phenomenological analyses are in progress.

## 5 Other phenomenological consequences

There are several other interesting consequences of the model which are currently under investigation. One of such consequences involves the phenomenology of the triplet Higgses that exist in this model:  $\tilde{\chi}$  and  $\xi$ . Since they carry electroweak quantum numbers, they can be produced at colliders such as the LHC or ILC. The various scalars in  $\tilde{\chi}$  couple to the mirror fermions through Eq. (8) and can possibly be searched for through the decays of the mirror fermions.  $\xi$  does not couple directly to fermions (SM and mirror) and the various components would decay either directly to a pair of electroweak gauge bosons either real or virtual.

The mirror fermions carry exactly the same quantum numbers as the SM fermions. They can be produced in exactly the same manner as the SM fermions at colliders. However their decays will be quite interesting. From Eq. (5), one can see that a charged mirror fermion can decay into its SM counterpart plus  $\phi_S$  which would be missing energy. This kind of decay for the charged mirror leptons has already been mentioned above (19).

Last but not least, vacuum stability considerations will link the masses of the scalar sector which now includes the triplet Higgses to those of the fermions (SM and mirror). This is under preparation.

## 6 Conclusion

- It is possible to have a seesaw mechanism in which the Majorana mass of the right-handed neutrinos can be of the order of the electroweak scale and, in fact, can be situated in a “narrow” range  $M_Z/2 < M_R < \Lambda_{EW}$ . There is *no* reason why it should be close to some GUT scale.
- The lepton-number violating processes coming from the “heavy” *non-sterile*  $\nu_R$ ’s can now be accessible *experimentally* at colliders! In contrast, in models where  $\nu_R$ ’s are SM singlets, it is problematic to both have a light neutrino and a non-negligible coupling between sterile and active neutrinos, resulting in a situation in which it might be extremely hard to detect lepton-number violating processes at the LHC for example <sup>5)</sup>.
- There is a rich spectrum of particles which can be tested in a not-too-distant future.

Below is a grossly incomplete list of references. My apologies for not being able to list all the references because of length restrictions.

## 7 Acknowledgements

I would like to thank Mario Greco and the organizers of La Thuile 07 for an exciting conference and the Aspen Center for Physics where part of this manuscript is written. This work is supported in parts by the US Department of Energy under grant No. DE-A505-89ER40518.

## References

1. P. Q. Hung, Phys. Lett. B**649**, 275 (2007) [arXiv:hep-ph/0612004].
2. See e.g. P. Q. Hung, Phys. Rev. D**67**, 095011 (2003) [arXiv:hep-ph/0210131].
3. P. Minkowski, Phys. Lett. B **67**, 421 (1977); M. Gell-Mann, P. Ramond and R. Slansky, in *Supergravity*, eds. P. van Nieuwenhuizen and D. Z. Freedman (North Holland 1979); T. Yanagida, in *Proceeding of Workshop on Unified Theory and Baryon Number in the Universe*, eds. O. Sawada and A. Sugamoto (KEK 1979); S. L. Glashow, *The future of elementary particle physics*, in *Proceedings of the 1979 Cargese Summer Institute on quarks and leptons* (M. Levy, J. -L. Basdevant, D. Speiser, J. Speiser, R. Gatsmans, and M. Jacob, eds.) Plenum Press, New York, 1980, p. 687; R. N. Mohapatra and G. Senjanović, Phys. Rev. Lett. **44**, 912 (1980); J. Schechter and J. W. F. Valle, Phys. Rev. D **22**, 2227 (1980). For recent reviews, see V. Barger, D. Marfatia, and K. Whisnant, Int. J. Mod. Phys. **E12**, 569 (2003) [arXiv:hep-ph/0308123]; R. N. Mohapatra *et al*, arXiv:hep-ph/0510213; G. Altarelli, arXiv:hep-ph/0611117, and references therein.
4. See e.g. Petr Vogel, arXiv:hep-ph/0611243; K. Zuber, Acta Phys. Polon. B**37**, 1905 (2006) [arXiv:nucl-ex/0610007], and references therein.
5. Jörn Kersten and Alexei Yu. Smirnov, arXiv:0705.3221v1, and references therein.
6. H. Georgi and M. Machacek, Nucl. Phys. **B262**, 463 (1985); R. S. Chivukula and H. Georgi, Phys. Lett. B **182**, 181 (1986); P. H. Frampton, M. C. Oh, and T. Yoshikawa, Phys. Rev. **D66**, 033007 (2002) [arXiv:hep-ph/0204273]. For a recent use of a Higgs triplet, see E. Ma and U. Sarkar, Phys. Lett. B **638**, 356 (2006) [arXiv:hep-ph/0602116].

7. P. Q. Hung, arXiv:hep-ph/0010126; P. Gu, X. Wang, and X. Zhang, Phys. Rev. **D68**, 087301 (2003); R. Fardon, A. E. Nelson, and N. Weiner, JCAP **0410**, 005 (2004). Cosmo MSW effects in these models were studied by Pham Quang Hung and Heinrich Päs, Mod. Phys. Lett. **A20**, 1209 (2005) [arXiv:astro-ph/0311131].